Higgs Property Measurements with the CMS detector

Lucas Kang (Johns Hopkins) (CMS collaboration)

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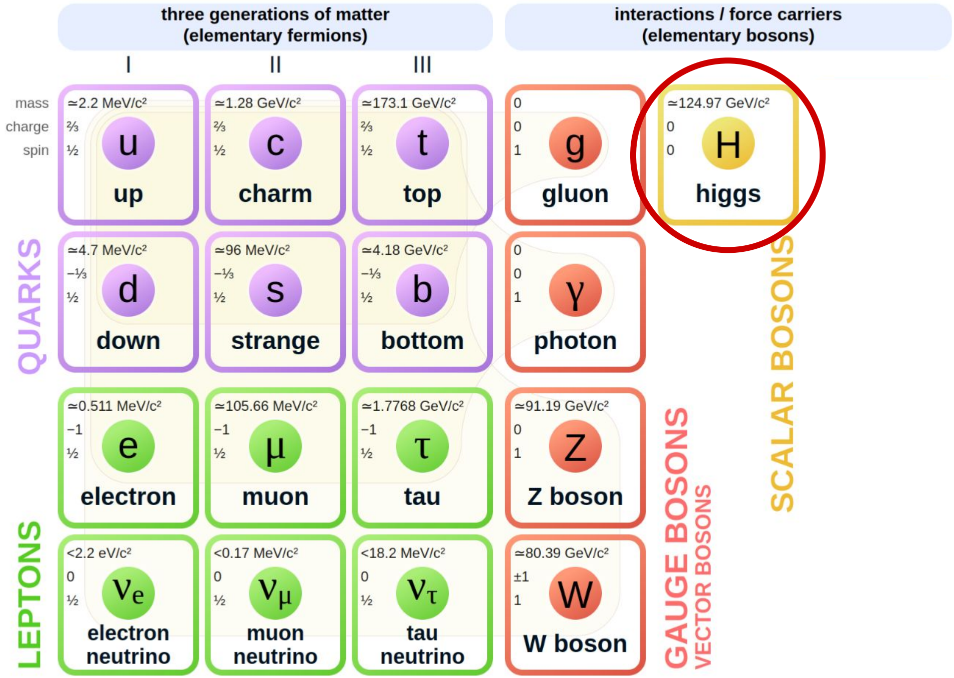
Northeastern University - ISEC Room 102

Outline

- Introduction
- Higgs Properties
  - Mass
  - Width
- Higgs Couplings & CP Structure
- Summary

Introduction

- Scalar with non-zero VEV
- EWSB and mass mechanism
- Last measured free parameter of the Standard Model
- Width is dependent on its couplings
  - Could probe new physics
- Precision measurements are crucial
  - Manage detector limitations



Measuring the Higgs - Mass

CMS-PAS-HIG-21-019

Prior analysis: JHEP 11 (2017) 047

Use the full Run 2 data set

Use four final state categories (4μ, 4e, 2μ2e, and 2e2μ) in on-shell

Events are classified into 9 categories based on their σ_{m4l}/m_{4l}

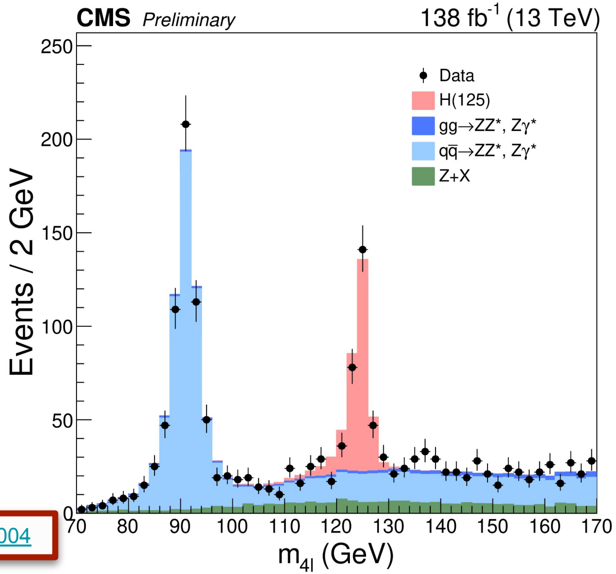
Ranges are found by splitting ggH (at 125 GeV) evenly into 9 bins

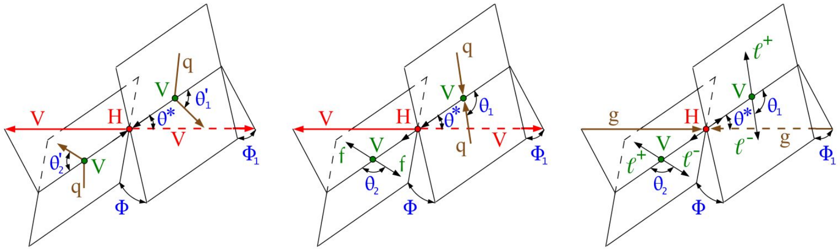
2D likelihood modelling $\mathcal{N} \times \mathcal{L}(m_{4l}, D_{bkg}^{kin})$

Using the matrix element-based discriminant:

$$\mathcal{D}_{bkg}^{kin} = \left[1 + \frac{\mathcal{P}_{bkg}^{q\bar{q}}(\vec{\Omega}^{H\to4\ell}|m_{4\ell})}{\mathcal{P}_{sig}^{gg}(\vec{\Omega}^{H\to4\ell}|m_{4\ell})}\right]^{-1}$$

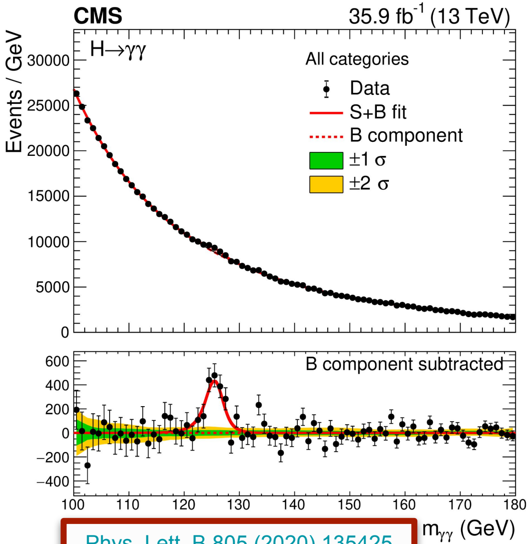
Phys. Rev. D 104 (2021) 052004





Measuring the Higgs - Mass

- Best measured with high mass resolution channels: 4l, $\gamma\gamma$
- 4l+$\gamma\gamma$ Run 1 + 2016: 125.38±0.14(0.11) GeV
- 4l Run 1 + 2: 125.08±0.10(stat)±0.05(syst) GeV



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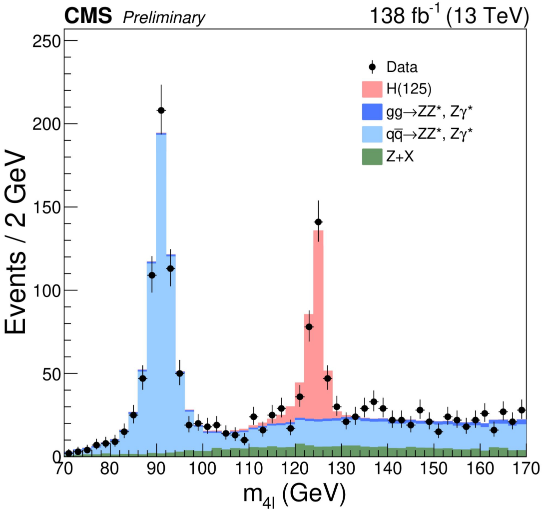
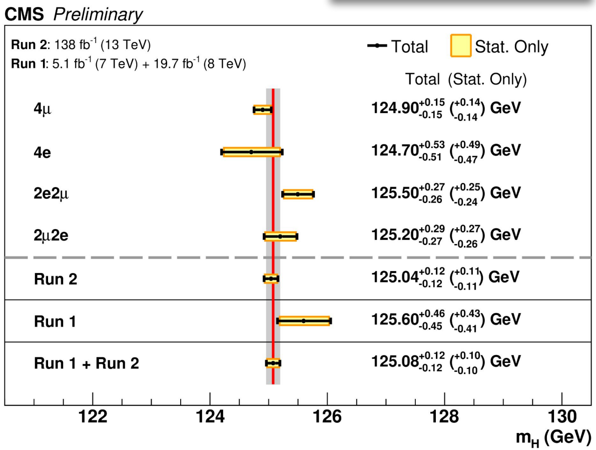
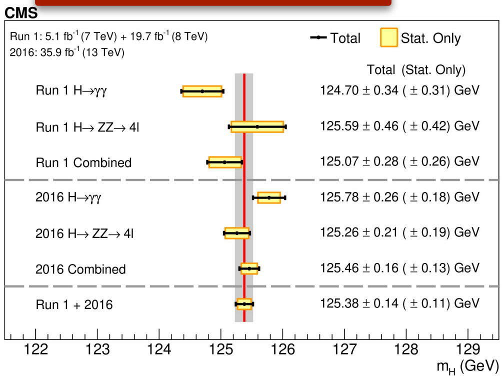
Phys. Lett. B 805 (2020) 135425





Parameter	Observed	Expected
m_{H} (GeV)	125.08 ± 0.12	±0.12



Measuring the Higgs - Width

- $\Gamma_{H,SM}$ = 4.07 MeV
- Direct measurement of the Higgs is limited by detector resolution
  - ~3×10^{-3} eV < Γ_H < 0.5 - 3 GeV

Parameter	Observed	Expected
m_H (GeV)	125.08 ± 0.12	± 0.12
on-shell Γ_H (MeV)	0^{+60}_{-0} $[0, 330]$	0^{+360}_{-0} $[0, 750]$

Mass and total width Γ_H measurements, showing the allowed 68% CL (central values with uncertainties) and 95% CL (in square brackets) intervals. Uncertainties are reported as a combination of statistical and systematic uncertainties.

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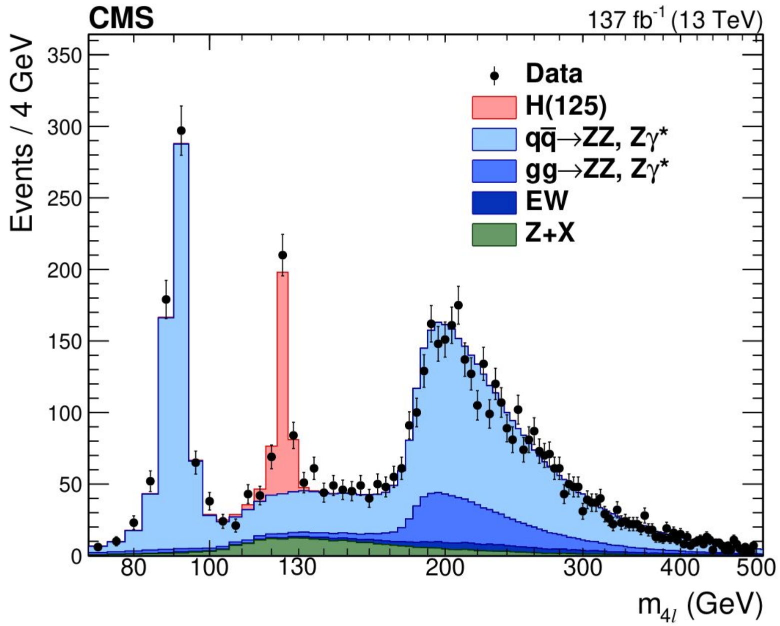

$H \to ZZ^{(*)} \to 4\ell$

$H^{(*)} \to ZZ \to 4\ell$

Eur. Phys. J. C 81 (2021) 488

Measuring the Higgs - Width

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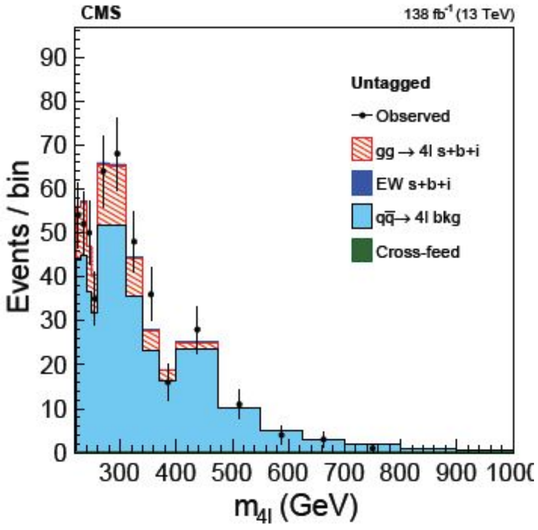
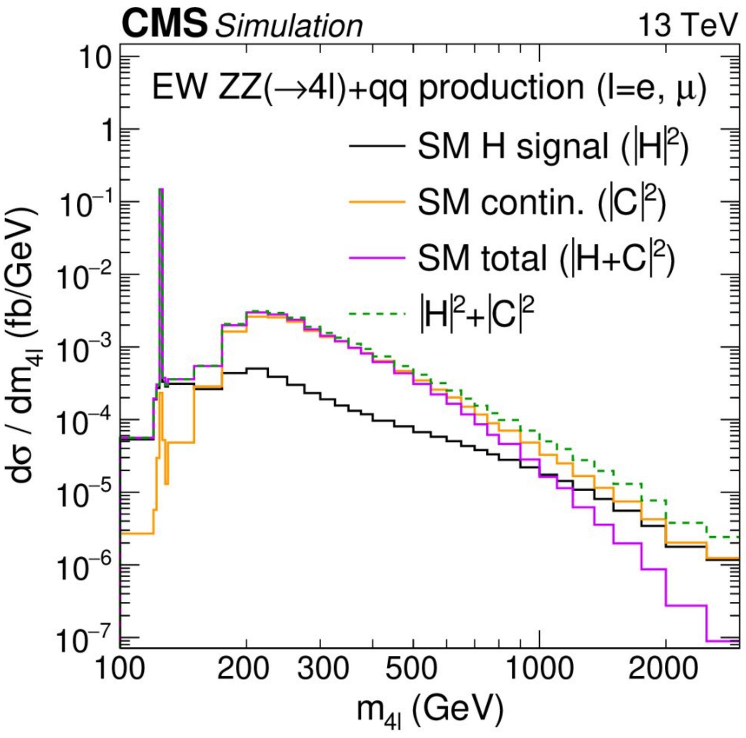
$$\sigma_H \sim \frac{g^2_{H\to gg} g^2_{H\to ZZ}}{\Gamma_H}$$

$$\sigma_{\rm off} \sim g^2_{H\to gg} g^2_{H\to ZZ}$$

$$\sigma_H \sim \sigma_H^{\rm SM}$$

$$\sigma_{\rm off} \sim \sigma_{\rm off}^{\rm SM} \frac{\Gamma_H}{\Gamma_H^{\rm SM}}$$





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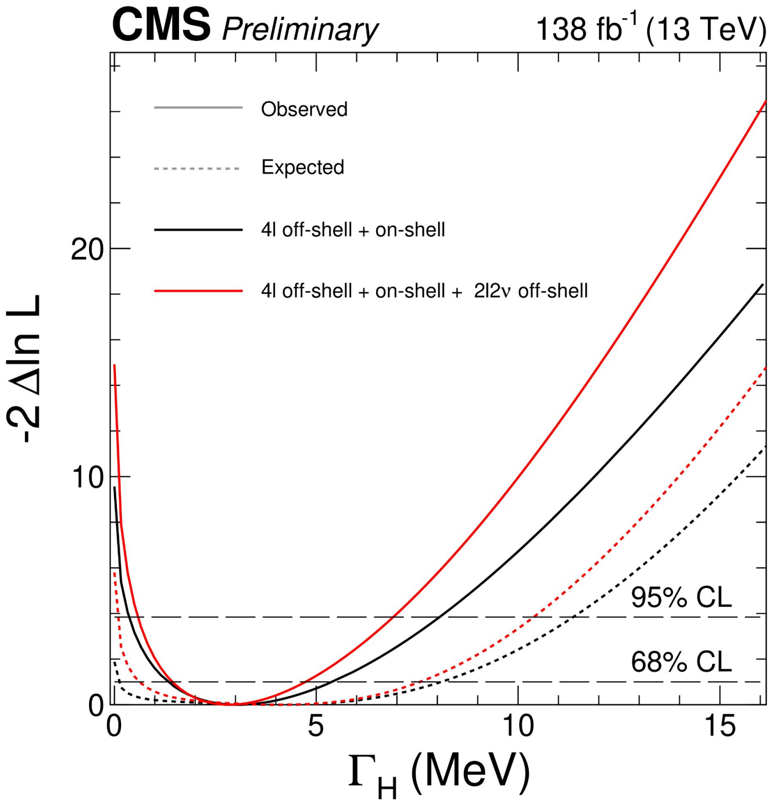
Measuring the Higgs - Width

- Off-shell Higgs production confirmed to 3.9σ

Parameter	Observed	Expected
$\mu^{\text{off-shell}}$	$0.64^{+0.50}_{-0.37}$ [0.06, 1.69]	$1.00^{+0.99}_{-0.97}$ [0.00, 2.80]
$\mu_{F}^{\text{off-shell}}$	$0.62^{+0.57}_{-0.41}$ [0.03, 1.81]	$1.00^{+1.05}_{-1.00}$ [0.00, 2.93]
$\mu_{V}^{\text{off-shell}}$	$0.69^{+1.32}_{-0.63}$ [0.00, 3.91]	$1.00^{+3.34}_{-1.00}$ [0.00, 7.65]

- Observed Γ_H via off-shell technique

Parameter	Observed	Expected
m_H (GeV)	125.08 ± 0.12	± 0.12
on-shell Γ_H (MeV)	0^{+60}_{-0} [0, 330]	0^{+360}_{-0} [0, 750]
off-shell Γ_H (MeV)	$2.9^{+2.3}_{-1.7}$ [0.3, 7.9]	$4.1^{+4.1}_{-4.0}$ [0.0, 11.7]



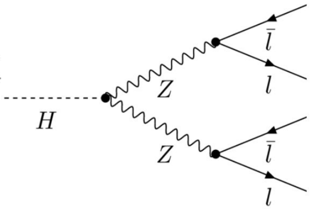
Measuring the Higgs - CP Structure

- Higgs is CP-even in the Standard Model
  - Observing any deviation would indicate BSM physics
- Strong motivation to search for CP-violating effects in Higgs couplings to fermions
- CP-odd contribution for Higgs couplings to bosons is largely suppressed

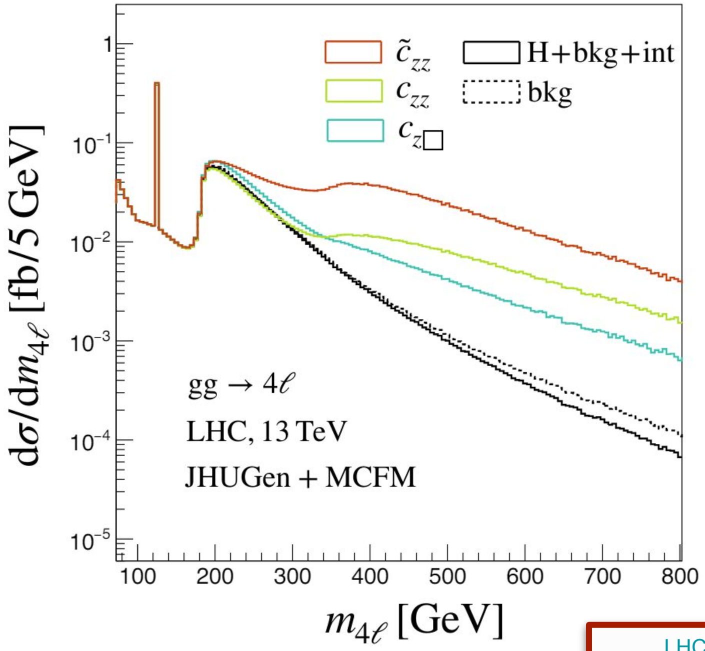
	Process to probe	Scale of CP-odd contribution
Fermion	Htt, $H\tau\tau$	O(1) Tree Level
Gauge boson	Hzz, Hww, $Hz\gamma$, $H\gamma\gamma$, Hgg	$O(1/\Lambda^2)$ Dim 6

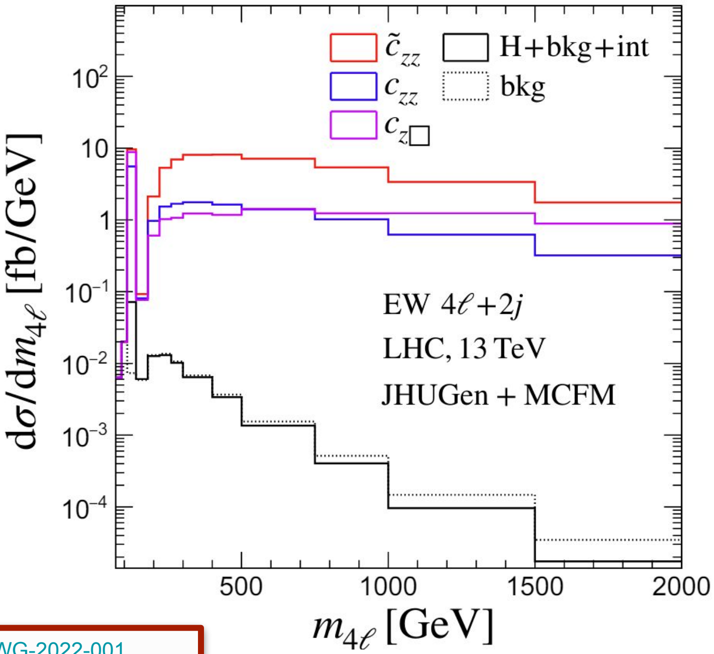
Higgs Couplings

$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

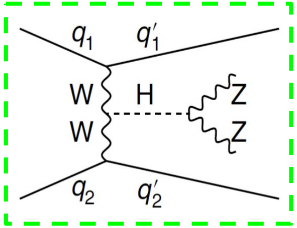


- VBF and VH processes have HVV vertices on the production side
- Anomalous EW production modes exaggerate the effect of any BSM terms in this decay amplitude

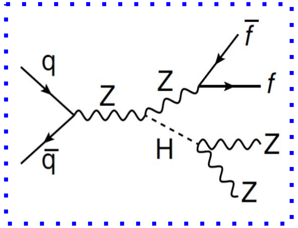




$q_1 q_2 \rightarrow q_1' q_2' H \rightarrow q_1' q_2' ZZ$:



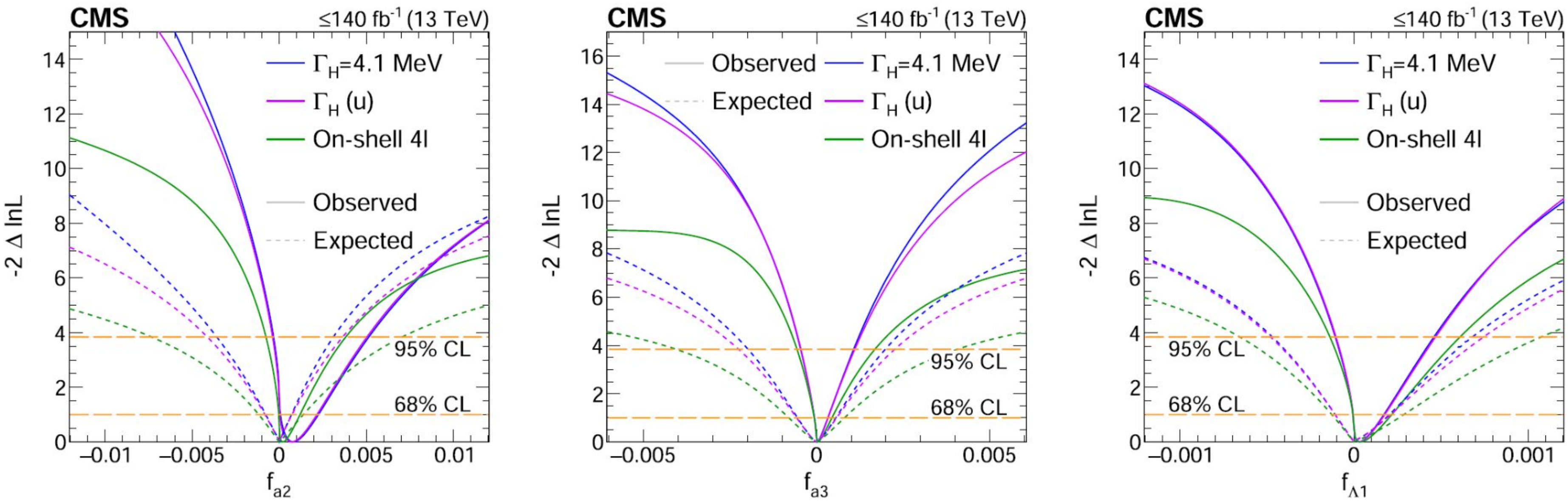
$q\bar{q} \rightarrow ZH \rightarrow ZZZ$:



[LHCHWG-2022-001]

Combined Constraints on Higgs Couplings

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_{j=1,2,3...} |a_j|^2 \sigma_j},$$



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HWW Constraints on Higgs Couplings

$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

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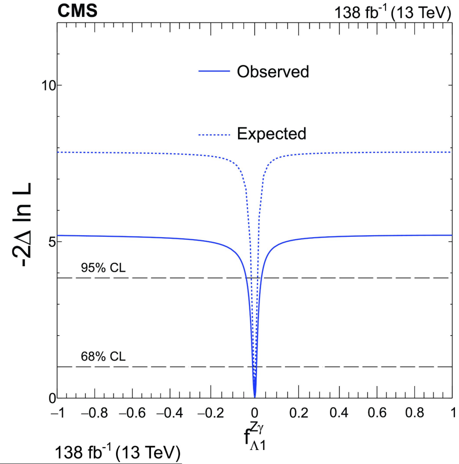
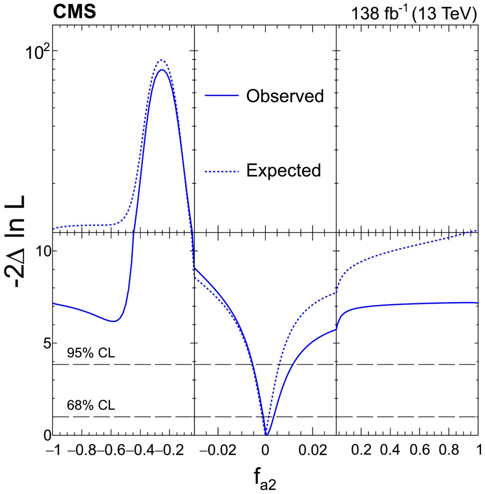
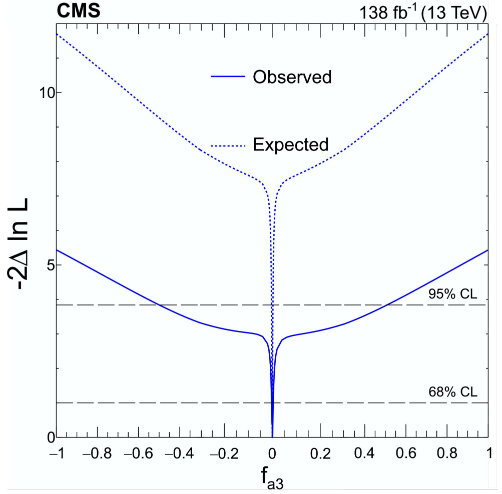
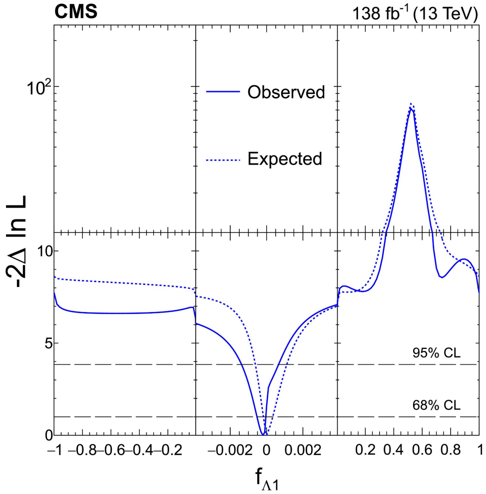
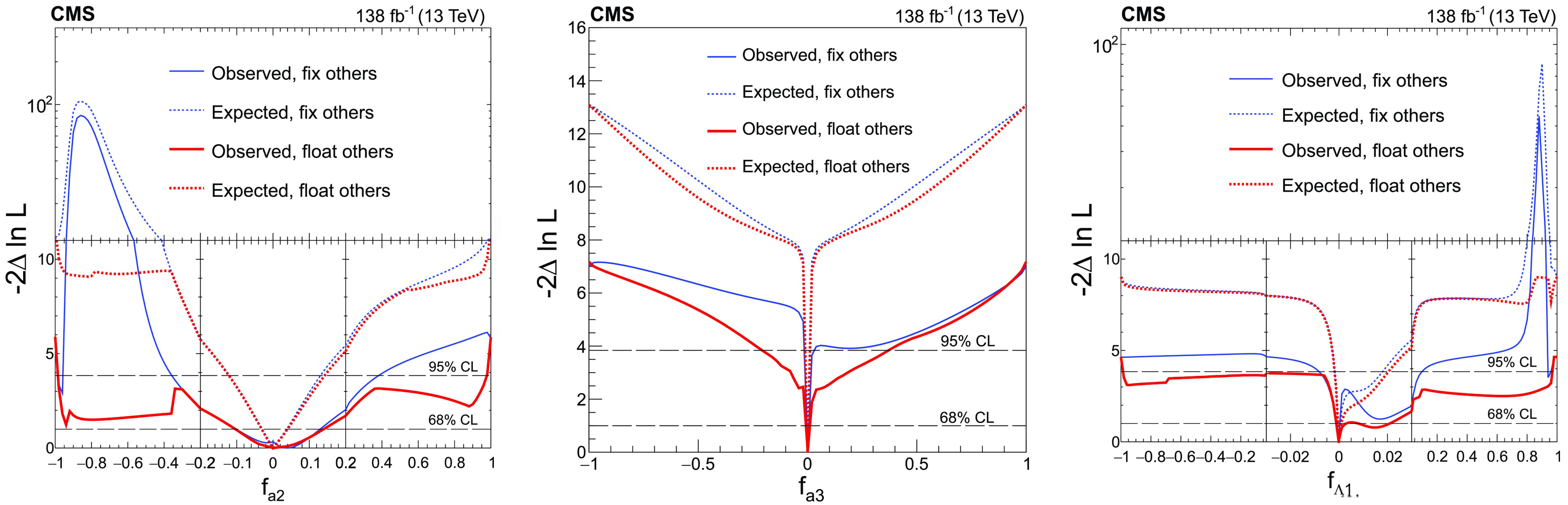








HWW Constraints on Higgs Couplings



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HWW Constraints on Higgs Couplings

Accepted in Eur. Phys. J. C

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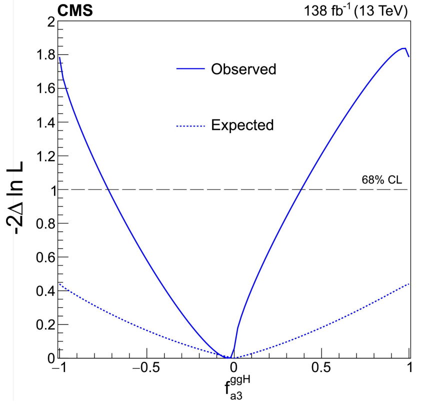
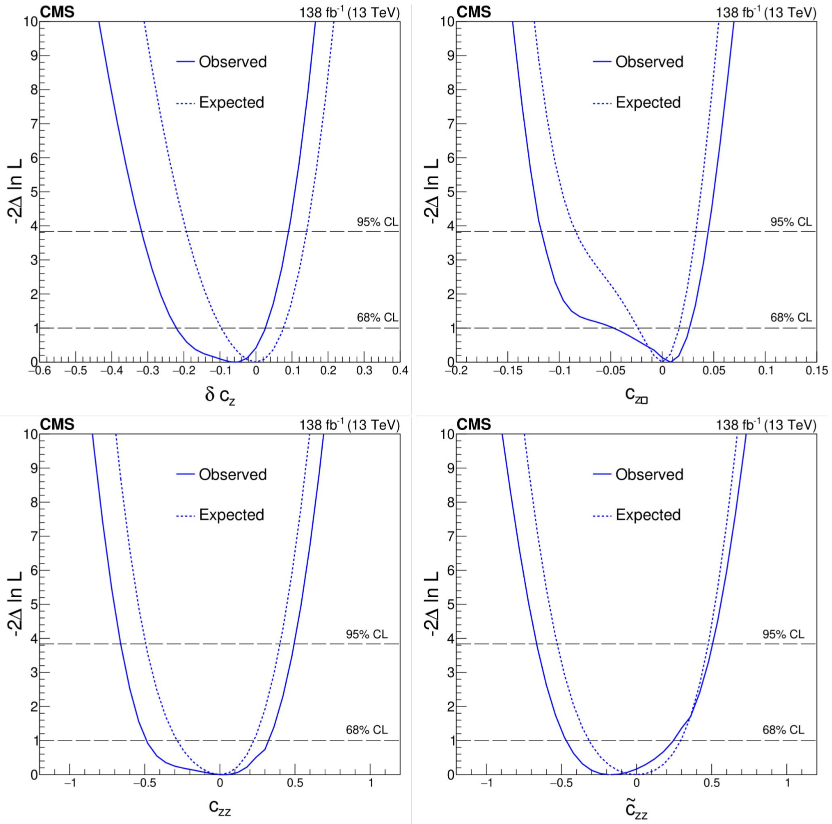


$$\delta c_z = \frac{1}{2} a_1^{ZZ} - 1,$$
$$c_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_2^{ZZ},$$
$$\tilde{c}_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_3^{ZZ},$$
$$c_{z\Box} = \frac{m_Z^2 s_w^2}{e^2} \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2},$$

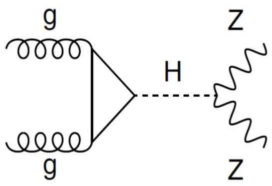


$H\tau\tau$ - CP Structure (HVV)

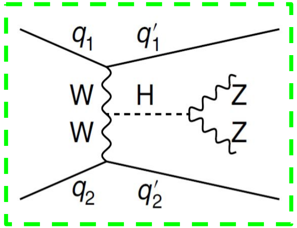
$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_{j=1,2,3\ldots} |a_j|^2 \sigma_j},$$

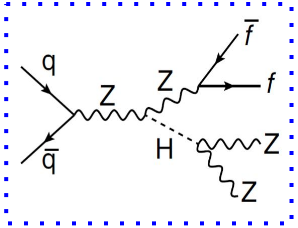
$gg \to H \to ZZ$:



$q_1 q_2 \to q_1' q_2' H \to q_1' q_2' ZZ$:



$q\bar{q} \to ZH \to ZZZ$:



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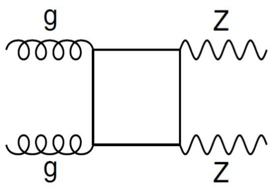
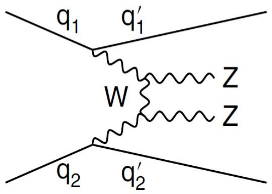
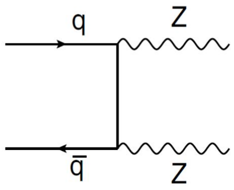
$gg \to ZZ$:

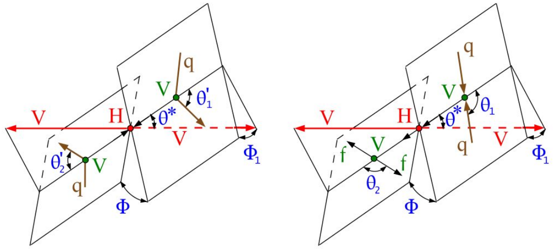


$q_1 q_2 \to q_1' q_2' ZZ$:



$q\bar{q} \to ZZ$:





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$H\tau\tau$ - CP Structure (Hgg)

$$\mu_{ggH} = 1.1068\kappa_t^2 + 0.0082 - 0.1150\kappa_t + 2.5717\tilde{\kappa}_t^2 + 1.0298(12\pi^2 c_{gg})^2 + 2.3170(8\pi^2\tilde{c}_{gg})^2 + 2.1357(12\pi^2 c_{gg})\kappa_t - 0.1109(12\pi^2 c_{gg}) + 4.8821(8\pi^2\tilde{c}_{gg})\tilde{\kappa}_t.$$

$$f_{a3}^{ggH} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2 + |a_3^{gg}|^2}\,\mathrm{sgn}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$$

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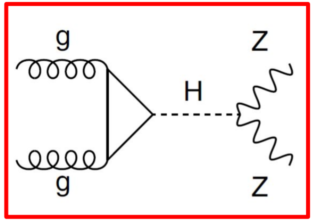
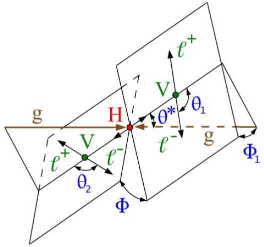
$gg \to H \to ZZ$:





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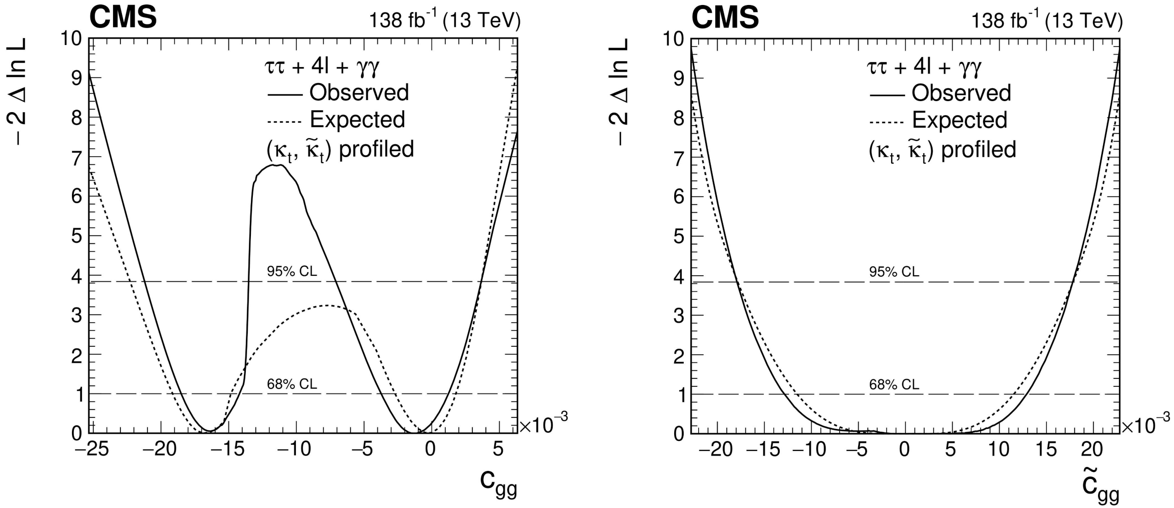
$$c_{gg} = -\frac{1}{2\pi\alpha_S} a_2^{gg},$$
$$\tilde{c}_{gg} = -\frac{1}{2\pi\alpha_S} a_3^{gg},$$



$H\tau\tau$ - CP Structure

$$a_i^{WW} = a_i^{ZZ} \text{ and } \kappa_i^{ZZ}/(\Lambda_1^{ZZ})^2 = \kappa_i^{WW}/(\Lambda_1^{WW})^2$$

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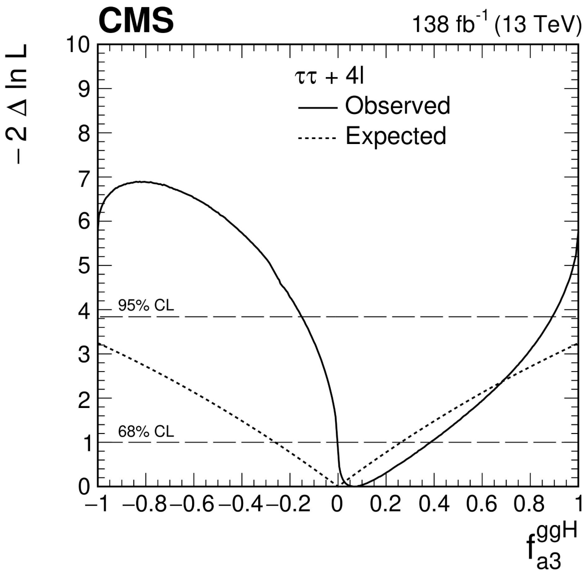
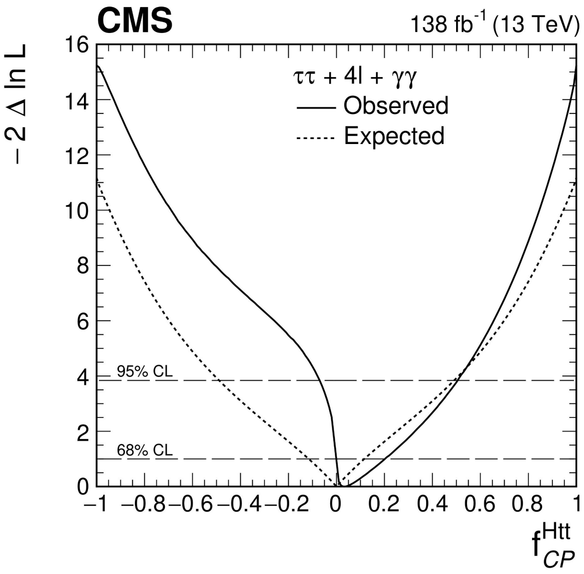
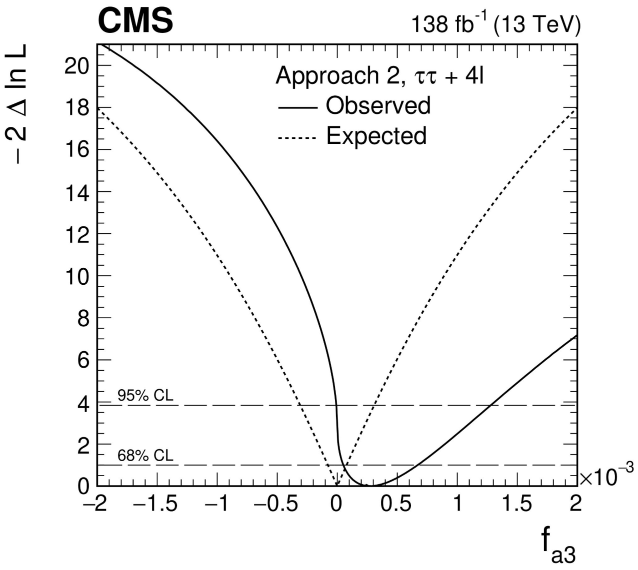




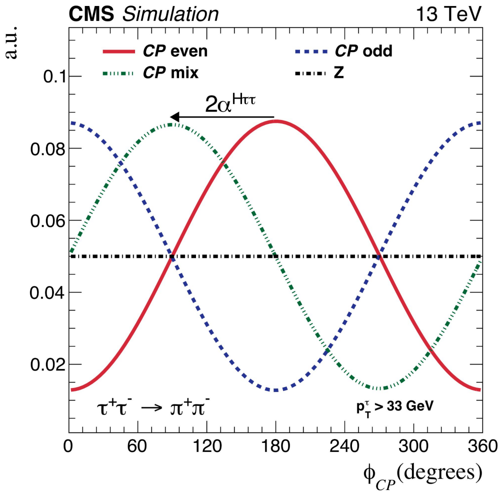


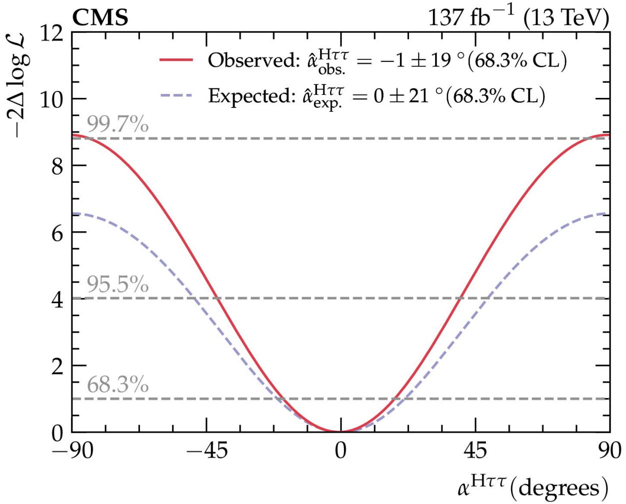
$H\tau\tau$ - CP Structure

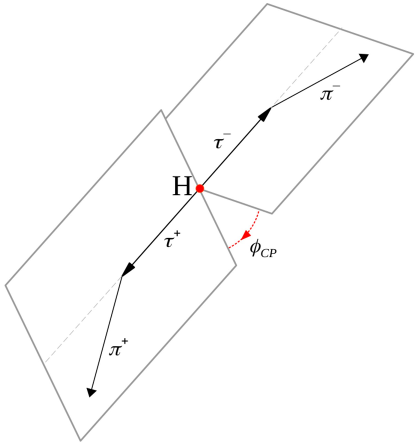
- Lagrangian for τ Yukawa coupling written as CP-even and CP-odd term

$$\mathcal{L}_Y = -\frac{m_\tau}{v} H(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i \gamma_5 \tau) \qquad \tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

- Use observable Φ_{CP} to probe the effective mixing angle $a^{H\tau\tau}$







JHEP 06 (2022) 012

ttH+tH - CP Structure

- Lagrangian for top Yukawa coupling parameterized similarly

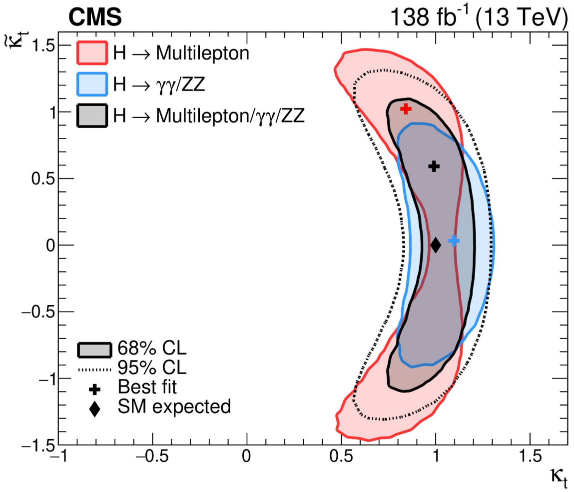
$$\mathcal{L}_{t\bar{t}H} = \frac{m_t}{v} \bar{\psi}_t (\kappa_t + i\gamma_5 \tilde{\kappa}_t) \psi_t H$$

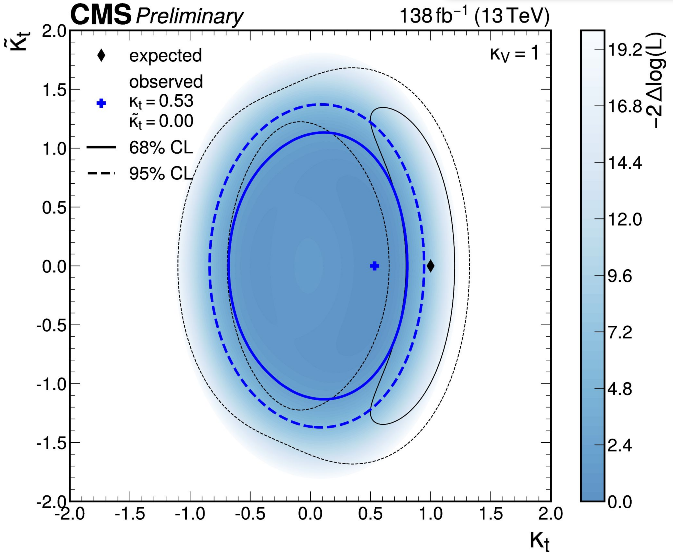
$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \text{sign}(\tilde{\kappa}_t / \kappa_t)$$

CMS-PAS-HIG-19-011

- Pure CP-odd disfavored at 3.2σ

JHEP 07 (2023) 092





Summary

- Higgs mass measurement: 125.08±0.12(0.10) GeV
- Higgs width measurement: Γ_H = 2.9+2.3−1.7 MeV
- Evidence of off-shell Higgs production at LHC: 4ℓ ⇒ 3.9σ
- Setting limits on HVV anomalous couplings via f_{ai} effective cross-section fractions
- CP violating effect probed in fermion sector, pure CP odd coupling excluded > 3σ

Thank You!

Backup

Future Outlook - SMEFT

SU(3) × SU(2) × U(1) invariant Lagrangian for H boson interactions with gauge bosons (mass-eigenstate parameterization):

$$\begin{aligned}\mathcal{L}_{\text{hvv}} = \; & \frac{h}{v}\Bigg[(1+\delta c_z)\frac{(g^2+g'^2)v^2}{4}Z_\mu Z_\mu + c_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu} + c_{z\Box}g^2 Z_\mu\partial_\nu Z_{\mu\nu} + \tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu} \\ & + (1+\delta c_w)\frac{g^2v^2}{2}W^+_\mu W^-_\mu + c_{ww}\frac{g^2}{2}W^+_{\mu\nu}W^-_{\mu\nu} + c_{w\Box}g^2\left(W^-_\mu\partial_\nu W^+_{\mu\nu} + \text{h.c.}\right) + \tilde{c}_{ww}\frac{g^2}{2}W^+_{\mu\nu}\tilde{W}^-_{\mu\nu} \\ & + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}A_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}\tilde{A}_{\mu\nu} + c_{\gamma\Box}gg'Z_\mu\partial_\nu A_{\mu\nu} \\ & + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^a_{\mu\nu} + \tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}\Bigg]\end{aligned}$$

We can relate the couplings in this Lagrangian to the terms which appear in calculations.
In particular, we have these relations to the amplitude parameterization:

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$$\delta c_z = \frac{1}{2}g_1^{ZZ} - 1\,, \quad c_{zz} = -\frac{2s_w^2c_w^2}{e^2}g_2^{ZZ}\,, \quad c_{z\Box} = \frac{M_Z^2 s_w^2}{e^2}\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}\,, \quad \tilde{c}_{zz} = -\frac{2s_w^2c_w^2}{e^2}g_4^{ZZ}\,,$$

$$\delta c_w = \frac{1}{2}g_1^{WW} - 1\,, \quad c_{ww} = -\frac{2s_w^2}{e^2}g_2^{WW}\,, \quad c_{w\Box} = \frac{M_W^2 s_w^2}{e^2}\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}\,, \quad \tilde{c}_{ww} = -\frac{2s_w^2}{e^2}g_4^{WW}\,,$$

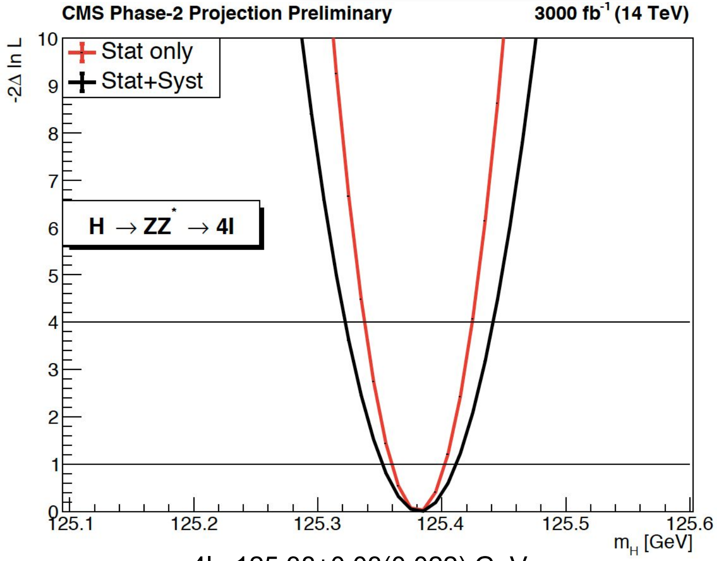
$$c_{z\gamma} = -\frac{2s_wc_w}{e^2}g_2^{Z\gamma}\,, \quad \tilde{c}_{z\gamma} = -\frac{2s_wc_w}{e^2}g_4^{Z\gamma}\,, \quad c_{\gamma\Box} = \frac{s_wc_w}{e^2}\frac{M_Z^2}{(\Lambda_1^{Z\gamma})^2}\kappa_2^{Z\gamma}\,,$$

$$c_{\gamma\gamma} = -\frac{2}{e^2}g_2^{\gamma\gamma}\,, \quad \tilde{c}_{\gamma\gamma} = -\frac{2}{e^2}g_4^{\gamma\gamma}\,, \quad c_{gg} = -\frac{2}{g_s^2}g_2^{gg}\,, \quad \tilde{c}_{gg} = -\frac{2}{g_s^2}g_4^{gg}\,.$$

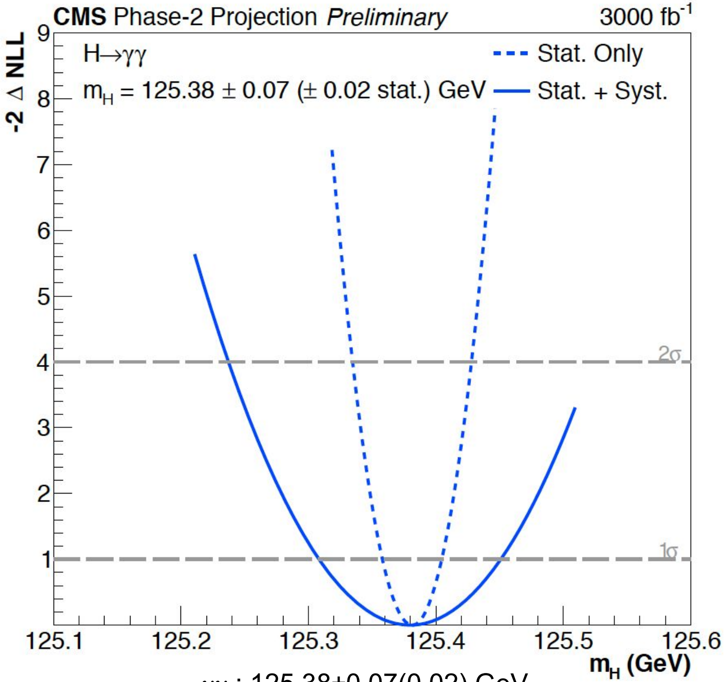
Future Outlook - High Luminosity

- Significantly higher pileup
- Enhanced corrections of ECAL due to statistics
- Higher acceptance for μ/e with new tracker
- Increased μ resolution

CMS-PAS-FTR-21-008



4l : 125.38±0.03(0.022) GeV



$\gamma\gamma$: 125.38±0.07(0.02) GeV

CMS-PAS-FTR-21-007